Ad-Hoc Networking: A Unified Evaluation Framework

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Abstract

Ad-hoc networks have become the focus of an increasing research volume, mostly because of the advantages of their *infrastructureless* nature. The system performance of an ad-hoc network depends on numerous attributes and factors, such as the *topology characteristics*, the *traffic scenarios* and the *node capabilities*. In this work we present a framework for the comprehensive analysis of ad-hoc networks as well as a framework for their categorization, applicable to the on-going research in the area, along with definitions for the network performance metrics.

I. Introduction

The emergence of a multitude of modern multimedia applications creates the demand for the evolving new network generation. The aim of this new network generation is to provide support for user applications everywhere, anytime. The "traditional networks" (wired, optical, etc.) are infrastructure-based and therefore require financial investments for infrastructure deployment as well as time consuming processes for the network to be operational. In *ad-hoc* networks a node can either enter or leave the network without any need for prior configuration. Consequently, no infrastructure is required as well as no lead time is needed for the network to become operational. Therefore, ad-hoc networks have become the focus of an increasing research volume.

The capability of using efficiently the system resources of an ad-hoc network, in order to achieve high *system performance*, depends on numerous factors and attributes and, more often than not, it is not easy to identify the problem and the constraints and objectives addressed by a proposed network structure. Therefore, an appropriate categorization of the ad-hoc networks according to the environment of operation, constraints, objectives and performance is required.

Few attempts so far, have tried to provide a framework for ad-hoc network categorization (examples are [1] [2] [3] [4] [5]). A complete framework requires not only the identification of the network characteristics that influence the performance, but also their concrete definitions. In [1] Perkins defined a number of important metrics and network characteristics, for ad-hoc networks, but neither distinction among them was clearly given, nor an indication of their relations. In [2] the performance metrics corresponding to the transient behavior were listed whereas in [3] and [5] a number of definitions for ad-hoc networks are given. In general, the related work in the area of ad-hoc networks provides specialized definitions for both performance metrics and network characteristics without clear distinctions between them. It is evident that there is a lack for a generalized categorization framework in the particular area.

The work presented here, provides a framework for comprehensive performance analysis of ad-hoc networks as well as a framework for their categorization. In this framework we itemize the performance metrics along with sets of attributes and factors which influence the system performance. Performance metrics are important to evaluate the behavior of the network through different operation phases. While for traditional networks, with a priori known network deployment, transient behavior is important only for recovery after failures, in ad-hoc networks the need for transient performance evaluation is inherently important.

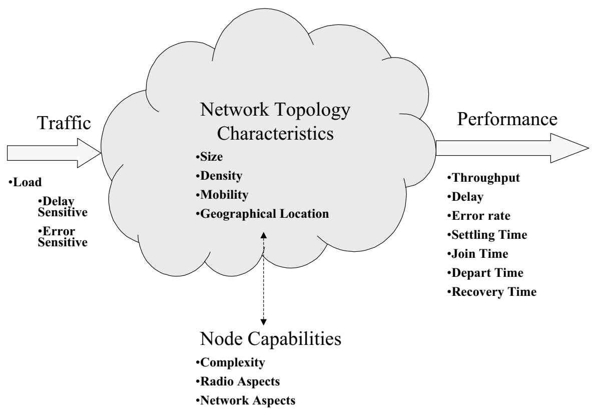

Figure 1. Framework Overview.

The values of performance metrics (i.e. the performance) are influenced by a number of attributes and factors that characterize the particular system. Attributes such as the *topology characteristics* of the ad-hoc network (network size, density, mobility) and factors like the *node capabilities*; in particular *radio aspects* (link, medium access, neighborhood discovery) as well as the *network aspects* (routing, clustering) and the *node complexity*, should be taken into account. Furthermore, the *traffic characteristics* (of the input traffic) affect the system behavior. In Figure 1 the basic framework for the interrelation among different attributes and performance metrics, is depicted.

The performance metrics are presented in Section II. The parameters used to describe certain attributes of the ad-hoc networks are presented in Section III. In Section IV the categorization of ad-hoc networks according to these attributes is presented. An example scenario that validates the analysis is presented in Section V. The conclusions can be seen in Section VI.

II. AD-HOC NETWORKING PERFORMANCE

We distinguish two main classes for the performance metrics used for evaluation and comparison purposes. The first one corresponds to the *steady state* mode of the system operation and it is called *steady state performance metrics*, or *stationary performance metrics*. A network is at a steady state mode when there is no erroneous situation, or if there was one and the system has long dealt with it; the effect of any behavioral "discontinuity" has been smoothed out. Thus, "steady-state" corresponds to the "long run average" values [5] of the performance metrics which are the "standard" metrics for the system performance comparison.

The second category corresponds to metrics that characterize the behavior of the system when it changes mode of operation. These metrics are called *transient performance metrics* and correspond to the *transient mode* of the network operation.

Both of these classes can be further itemized for the *Radio Aspects* as well as the *Network Aspects*. The Radio Aspects correspond to the actual "physical" connection of a node with its "neighbor" nodes. This includes the *Physical* (PHY) layer as well as the *Medium Access Control* (MAC) layer. The Network Aspects correspond to a more abstract, or logical, clustering or subnetwork view of the overall network (e.g. IP layer).

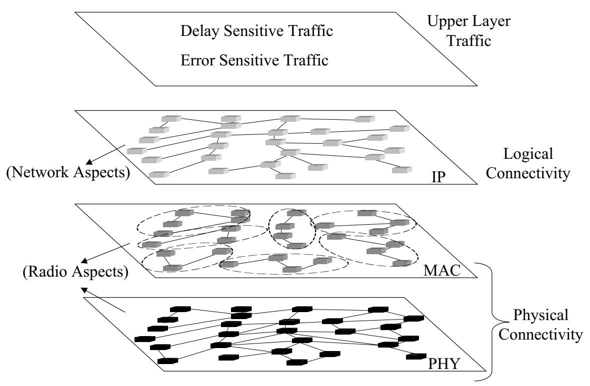

Figure 2. Physical and Logical Connectivity Representation for an Ad-Hoc Network.

Figure 2 is a graphical representation of the layering structure that correspond to both Radio and Network Aspects. PHY determines whether two nodes can establish peer-to-peer communication or not, whereas MAC is responsible to identify which of the set of nodes is desirable to establish such communication; we call this *physical connectivity*. At the Network Aspects, in the IP protocol suite, the routes suitable for particular application traffic (traffic characteristics as well as source and destination) are determined, based on the physical connectivity information. The set of routes comprises the *logical connectivity* information.

The logical connectivity corresponds to multihop information; the set of nodes that a particular data packet will be forwarded through inside the network, is maintained. Usually, at the MAC layer, no such information is maintained, since only one hop information is required at MAC layer. On the other hand, in ad-hoc networks the two hop information can be critical for the increment of the MAC efficiency (hidden/exposed terminal problem, as it will be shown next). Therefore, multihop information will be beneficial for *joint optimization* of both Radio and Network Aspects.

A. Steady State Performance Metrics

The system resources are *frequency*, *time*, *space* and, possibly, *Multiple Access/Multiuser* techniques. The objective is to exploit these resources as efficiently as possible thereby achieving high performance within the constraints. In ad-hoc networks rapid changes in physical connectivity are possible due to the lack of prior configuration[1].

An example for physical connectivity can be seen in Figure 3, where a network is depicted at a specific time instance. Each node is supported by omni-directional antenna and a line between two nodes represents the fact that the nodes can listen to each other. These nodes are also called *one hop* nodes. In general[2], collision, for a given transmission, takes place when the destination node transmits and/or when another node within one hop from the destination also transmits. The latter case is the so-called *hidden/exposed terminal* problem and it is an important reason for performance degradation in ad-hoc networks. In the example depicted in Figure 3, transmission from node 8 to node 13 is denoted with a white arrow, while black arrows denote the transmissions that should not take place in order transmission 8 to 13 to be successful; all other transmissions do not affect transmission 8 to 13.

One of the objectives for ad-hoc networks is to decide whether a transmission should take place, while the node locations change by time. This is a difficult task for MAC in ad-hoc networks and requires information of the neighborhood of a node[3] to avoid being influenced by the hidden/exposed node problem. Several handshake techniques have been introduced that allow only certain sets of transmission to take place, like the *Request-To-Send/Clear-To-Send* (RTS/CTS) mechanism.

[1]The rapidity of changes depends on the degree of mobility.

[2]In this case we assume a contention-based MAC without multiuser capabilities.

[3]The neighborhood of a node is the set of one hop nodes of all the one hop away nodes of the particular node.

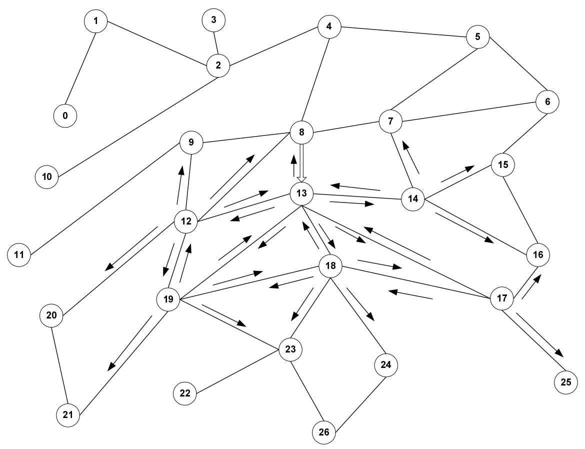

Figure 3. Example Network for Transmission from node 8 to node 13.

A.1 Radio Aspects

At the MAC layer, a fraction of the *physical resources* provided by PHY ends up being used. For this we use *efficiency/utilization* U_R of the Radio in bits/sec/Hz, as a normalized metric for the efficiency of using the physical resources[4].

The resources are not used only for data transfer, but also for control information required for the MAC operation. Note that the control information originated from logical connectivity is treated as data by Radio Aspects. Let *throughput* of the Radio (Th_R), a non-normalized metric, denote the average amount of successfully transmitted packets by appropriately defined MAC per time unit. *Utilization/efficiency* U_R^i refers to information bearing in bits/sec/Hz and corresponds to information bearing throughput appropriately normalized. Note that it will be $U_R^i < U_R$ due to the existence of control information necessary for the MAC operation.

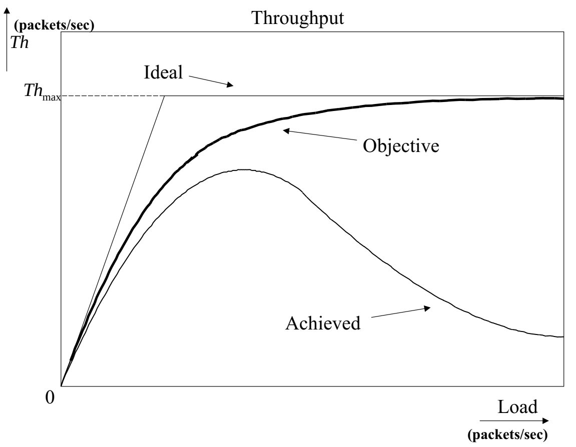

Figure 4. Ideal, Objective and Achieved Throughput (T) as a function of load, for a specific traffic type.

[4]It is important to note that the value of the performance metrics is possible to be calculated as the average for the "long run" behavior of the system. Useful additional parameters are the minimum and the maximum value for each performance metric. Ideally, the distribution of the values provides a full understanding of the system performance metric.

Figure 4 depicts throughput as a function of load. As load increases and the maximum value for throughput Th_{max} is achieved the *ideal* behavior is shown. The *objective* is to achieve throughput results close to the ideal. In traditional networks this is achievable in heavy load conditions, by the use of TDMA access schemes. While TDMA is rather difficult to be used in ad-hoc networks due to the lack of prior configuration, there is an increasing research interest in the area [13] [14]. In case of contention-based access schemes (e.g. CSMA) the heavy load leads to a decrease of the *achieved* throughput.

Another important parameter is the delay for each data packet to be transmitted across a link. We define *delay* (D_R) as the time required for a data unit arriving at the MAC layer, to be successfully transmitted across the corresponded link and through the corresponded MAC layer.

It has been documented that the MAC protocol can treat nodes in an unfair way [6]; *fairness* does not mean equality. For nodes that have identical traffic characteristics and priority requirements, the amount of resources allocated by the MAC should be equal in order for the system to be fair.

Finally, *Power Consumption Limitations* is another important factor for the evaluation of an ad-hoc network and it is related to the node capabilities, as it can be seen in Section III.

A.2 Network Aspects

For the Network Aspects, we define as throughput Th_N the (average) rate of data forwarded by the network to the appropriate destination; the appropriate destination is either the destination node or the network boundaries in case the destination node does not belong to the considered network[5].

Delay D_N is defined as the time[6] required for data packets (e.g. IP datagram) to be served by the network.

Packet Loss Rate (PLR_N) is the fraction of data packets failed to be delivered by the network. Note that if PLR_N is increased this does not affect D_N. On the other hand, the delay at higher layers is influenced. For example, as in Figure 2, for the IP protocol suite, if the Transport layer protocol is TCP then we have error sensitive traffic and the delay increases due to the retransmission of the lost packets. If it is UDP then we do not have error sensitive traffic but rather, delay sensitive and the delay does not increase (at this layer).

Ad-hoc networks require the exchange of certain signaling messages in order to support mobility aspects (for example signaling for the construction of routing tables). The amount of the control information depends on the particular routing protocol as well as on the mode of the system. For example, for a network with high mobility, route updates take place too often (DSDV, WRP, AODV, DSR, etc. [15]

[5]Efficiency/utilization are hard to be measured/calculated for the Network Aspects, since the "network capacity" cannot easily be calculated.

[6]For both Th_N and D_N the average as well as the minimum and maximum values can be considered.

TABLE I

PERFORMANCE METRICS.

Network Mode	**Metrics**	**Aspects**	
		Radio	Network
Steady State	Th	Th_R	Th_N
	D	D_R	D_N
	U	U_R	-
	$U^\imath$	$U_R^\imath$	-
	PLR	-	PLR_N
	Fairness	$\surd$	-
	Power Consumption Limitations	$\surd$	$\surd$
Transient	Network Settling Time	$\surd$	$\surd$
	Network Join Time	$\surd$	$\surd$
	Network Depart Time	$\surd$	$\surd$
	Network Recovery Time	$\surd$	$\surd$
	Route Update Time	-	$\surd$

[16]). This increases the amount of control information using the system resources, resulting to a decrease of the available throughput. Let Th_N^i and Th_N^c denote the throughput used for data packets and control packets respectively. Obviously, $Th_N^i + Th_N^c = Th_N$. For different routing protocols and different modes of the network operation Th_N^c varies and, consequently, Th_N^i varies as well. Ideally, Th_N^i is required to be close to Th_N. We should emphasize that throughput performance is conditioned on the traffic type and the corresponding QoS. Thus, Th_N will probably be lower for delay sensitive traffic than for error sensitive.

Additionally, the transient performance metrics presented in the following section are influenced as well (for example, the time until the route tables are updated increases).

B. Transient Performance Metrics

For both Radio Aspects and the Network Aspects the following transient performance metrics should be considered describing the system when it is changing the corresponding mode of operation.

- *Network Settling Time* is the time required for a set of nodes to organize itself and transmit the first message reliably.
- *Network Join Time* is the time required for a node to be part of the ad-hoc network.
- *Network Depart Time* is the time required for the network to understand the departure of a node. The departure of a node maybe due to mobility reasons or due to a failure.
- *Network Recovery Time* is the time required for a part of the network to become operational after an erroneous situation.
- *Route Update Time* is the time between the event of join, depart of failure or a node (that leads to a need for reconstruction of the routing tables) and the completeness of the routing reconstruction.

Summary of performance metrics exists in Table I.

III. NETWORK ATTRIBUTES

The performance metrics already described, are influenced by certain parameters that characterize the ad-hoc networks. Three different sets of parameters can be distinguished. The first corresponds to the *topology characteristics*; the second corresponds to the *traffic characteristics* of the considered applications; the third describes the *node capabilities*.

A. Topology Characteristics

Each topology can be represented as a graph $G(V_t, E_t)$, at a specific time instance t, where V_t corresponds to the set of nodes and E_t to the set of links between nodes at the specific time instance t. A link exists between two nodes if a direct communication is achievable in terms of Radio Aspects. If this is the case then these two nodes are called *neighbor nodes*. In case a node is capable of selecting the set of neighbor nodes that a direct communication is possible to be established, then this node is equiped with *topology control* capabilities (for example when adaptive antennas are used). The benefit of topology control is obvious since the number of interfering neighbor nodes can be smaller. On the other hand the energy consumption increases as well as the node complexity.

The *network size* corresponds to the geographical area occupied by the network. The *network density* refers to the number of nodes present in the geographical area occupied by the network[7]. The *mobility* of the nodes is reflected to the changes in the topology graph $G(V_t, E_t)$ as nodes move, depart or appear at the network (see Figure 1).

B. Traffic Scenarios

The traffic characteristics of each application are rather important. The *load* of the applications is a rather important parameter. It corresponds to the actual amount of data that need to be delivered in one time instance.

There are two major categories of application traffic. The first corresponds to traffic for *delay sensitive* applications while the second corresponds to traffic for *error sensitive* applications.

C. Node Capabilities

Each node is possible to have different capabilities. Therefore, it is important for each node and each layer (Radio and Network Aspects) to employ algorithms that take into consideration certain input parameters.

For the Radio Aspects it is acceptable to take into consideration the *link quality* factor. Two elements characterize the link quality: the *bit-rate* and the *error bit-rate*. The

[7]This assumes uniform node distribution; other distributions can also exist.

physical topology awareness is another significant factor. Control information is required for each node in order to be able to gain information for its neighborhood. The degree of change of the neighborhood depends on *mobility*, is an important feature in ad-hoc networks. *MAC/PHY interaction* can be interpreted as the adaptation to the radio communication environment like the use of directional antennas. Other important factors are the *power constraints*, the *QoS support* (different priorities for different data sessions to satisfy QoS) and *security*[8].

Important factors for Network Aspects are the *physical topology knowledge*, the *mobility*, the *interaction with radio aspects*, the *power constraints*, *QoS support* as well as *security*.

Node complexity indirectly describes the capability of a node to support the already described functionality. Obviously, the extend to which the already mentioned factors are taken into consideration increases node complexity that corresponds to the "device capabilities" of a node, in terms of *processing power*, *physical memory* and *battery capabilities*[9]. Processing power and physical memory are required to support both Radio and Networking aspects. Additionally, the provided battery should be capable to support the device for a time period that is satisfactory for the user. Special care should be given at this point, to the device characteristics, since heavy equipments are not suitable for mobile use.

IV. A Classification of Ad-Hoc Networks Research Work

Table II provides a summary of the Network Characteristics already presented. The particular table will be the basis to categorize the various ad-hoc networks that are already implemented or proposed.

While much work has been performed in the 70s and 80s, most of the recent work on ad-hoc has been carried out under the MANET (Mobile Ad-Hoc Networks) group, [8], where the focus is mostly on the Network Aspects. Relatively small networks are considered, where the density of the network and the corresponded mobility are comparatively high. From the ad-hoc cluster of the IST projects the BroadWay IST-2001-32686 is selected for categorization. The classification of BroadWay, [9], (IST-2001-32686), can be seen in Table II as well as PACWOMAN, [10], (IST-2001-34157), the WIND-FLEX, [11], (IST-1999-10025) and MIND (BRAIN), [12], (IST-2000-28584). Additionally, the example topology independent (TopInd) scenario (that will be presented in Section V) is depicted in Table II.

BroadWay focuses on small/medium network sizes (equivalent to the network size of HiperLAN/2 [7]). The focus of the project is to offload the 5 GHz standard wireless LAN mode of operation by employing ad-hoc networking at 60 GHz. Therefore, the innovative elements of the project are applicable for high density networks with low mobility. PACWOMAN is destined for small areas (PAN size) and is aware of power constraints. WIND-FLEX is mostly an air-interface project and therefore, the node capabilities for Radio Aspects as well as for Network Aspects are limited. More details are depicted in Table II.

V. Example Scenario

A simulation scenario is presented here for a network that can be categorized accordingly and thus the simulation serves as an indirect proof of the applicability of the proposed framework. For this scenario a MAC protocol ([13], [14])[10] is considered and therefore, the focus is not on the Network Aspects but on the Radio Aspects. The particular MAC maintains a minimum guaranteed throughput, *independently* of the physical connectivity characteristics, if the maximum number of nodes present in the network as well as the maximum number of neighbor nodes for a node, remain constant. In fact the achieved throughput depends on the physical connectivity characteristics even though no such knowledge is required.

Error sensitive traffic scenarios are considered for heavy traffic demands, in the sense that a node is willing to transmit during any time slot. The node capabilities are limited and omnidirectional antennas are used. Node complexity characteristics are assumed to play no role for the operation of the network.

A. MAC Description

The implemented topology independent MAC protocol is based on [13]. A frame of length L was selected according to the algorithm presented in [14]. Errors were considered only for the case where a collision takes place. Scheduling time slots are assigned in such a way that it is assured that even for the worst case (in terms of traffic requirements) there will be at least one time slot in each frame that the node will transmit collision-free ([13] [14]).

B. Simulation Results

The fact that the minimum guaranteed throughput achievable by MAC protocol is independent of the topology, does not mean that the topology characteristics do not influence the throughput. In particular, as the number of nodes present in the network remains constant but the density of the topology increases (the geographical area occupied by the network decreases) the throughput decreases.

Figure 5 the results for a network that the number of present nodes (N) is 100. N_D is a maximum number of neighbors that a node can have. Both N and N_D are important for the calculation of frame L and the set of assigned time slots [13] [14]. The attribute *Neighborhood Density* is defined as the average number of neighbor nodes for each node divided by N_D.

[8] In ad-hoc network, due to the lak of prior configuration, the identification of unauthorized nodes is difficult.

[9] *Network Lifetime* can be defined as the time that an ad-hoc network remains operational; it is closely related to the battery capabilities of the nodes, as well as other procedures targeting power optimization.

[10] The term *topology independent* is not appropriate within the framework of this paper.

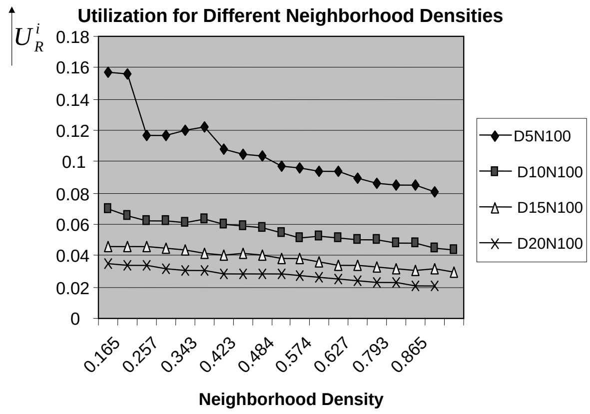

Figure 5. Simulation Scenario for various neighborhood density.

The results depicted in Figure 5 present four different cases for the network of 100 nodes. It is clear that as the number of links between nodes increases (neighborhood density for a particular N_D) U_R^i decreases. U_R^i is the percentage of the successfully utlized time slots[11]. Due to the topology independent nature of the MAC protocol, mobility affects the throughput only in the case where the topology density changes. Therefore, the results depicted in Figure 5 can be considered as an indirect impact of mobility over throughput, as well.

VI. Conclusions

In this paper we have presented definitions for the network performance metrics for both steady state and transient modes. Additionally, a framework for comprehensive analysis of ad-hoc networks was provided, as well as a framework for their classification.

Attributes and factors that influence the system performance were presented, along with a classification of various research projects. Finally, simulation results demonstrated how a network attribute (topology density) affects a system performance metric (utilization).

VII. Acknowledgements

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[11] The reason for this is that for this scenario the physical layer parameters remain constant.